BSM in Rare Charm Decays

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Aspects of Symmetry

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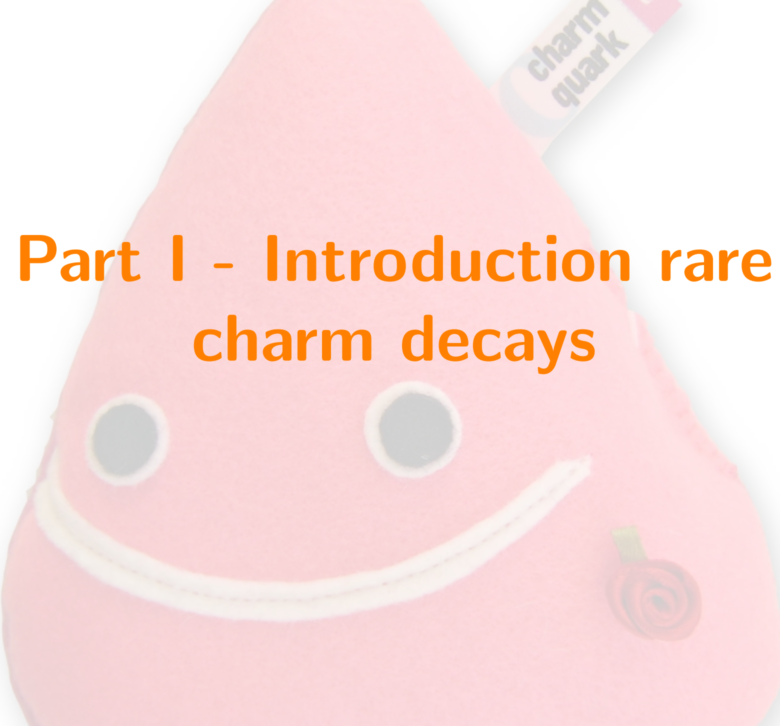
technische universität
dortmund

REGIONAL DOCTORAL PROGRAM IN THEORETICAL AND EXPERIMENTAL PARTICLE PHYSICS

Outline

- Part I - Introduction to rare charm decays
  - Effective field theory framework
  - Null test overview
- Part II - Null test observables
  - Angular observables
  - CP–violation
- Part III - Dineutrino modes
  - Flavor probes via $SU(2)_L$-link
- Outlook

Part I - Introduction rare charm decays



$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left[\sum_{i=7,9,10,S,P}(C_i O_i + C_i' O_i') + \sum_{i=T,T5} C_i O_i\right],$$

$$O_7 = \frac{m_c}{e}(\bar{u}_L \sigma_{\mu\nu} c_R) F^{\mu\nu},$$

$$O_9 = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \ell), \quad O_{10} = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

$$O_S = (\bar{u}_L c_R)(\bar{\ell}\ell), \quad O_P = (\bar{u}_L c_R)(\bar{\ell}\gamma_5 \ell),$$

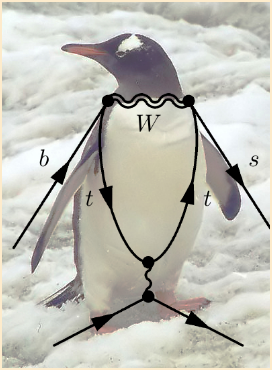
$$O_T = \frac{1}{2}(\bar{u}\sigma_{\mu\nu} c)(\bar{\ell}\sigma^{\mu\nu}\ell), \, O_{T5} = \frac{1}{2}(\bar{u}\sigma_{\mu\nu} c)(\bar{\ell}\sigma^{\mu\nu}\gamma_5 \ell).$$

- Primed operators obtained with $L \leftrightarrow R$

Similar to b-physics, BUT...

EFT at the charm scale de Boer, (2017), PhD thesis, TU Dortmund

What is the difference between $b \to s$ and $c \to u$ penguins?



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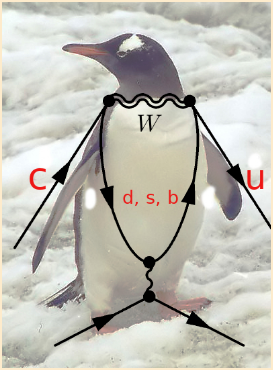

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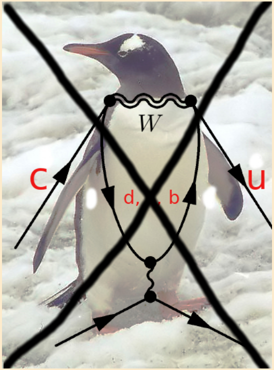
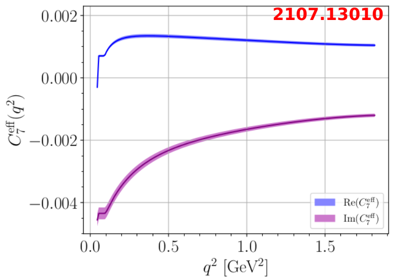
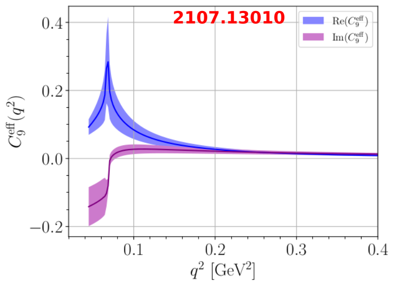


- Light quark masses need to be set to zero at μ_W
- Effective GIM-mechanism kills $C_{7,9,10}$ at μ_W
- $C_{7,9}^{\text{eff}}$ are induced by RG running to μ_c
- $C_{10}(\mu_c) = 0$

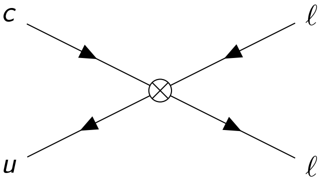




- $C_7^{\text{eff}} = \mathcal{O}(10^{-3})$, $C_9^{\text{eff}} = \mathcal{O}(10^{-2})$.
- $C_{10}^{(\prime)} = C_S^{(\prime)} = C_P^{(\prime)} = 0$ and $C_T = C_{T5} = 0$

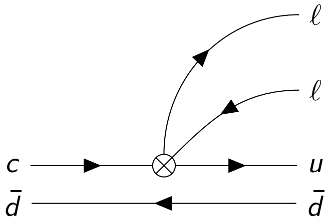
Rare charm decays

- $D^0 \to \ell\ell$



Rare charm decays

- $D^0 \to \ell\ell$
- $D^+ \to \pi^+\ell\ell$



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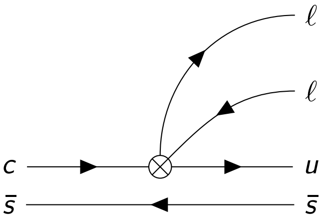

Rare charm decays

- $D^0 \to \ell\ell$
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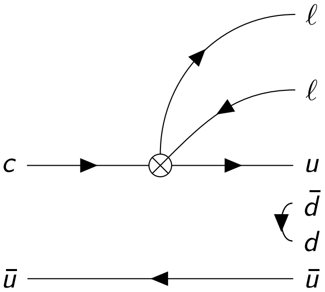
- $D_s^+ \to K^+\ell\ell$
- $D^0 \to \pi^+\pi^-\ell\ell$



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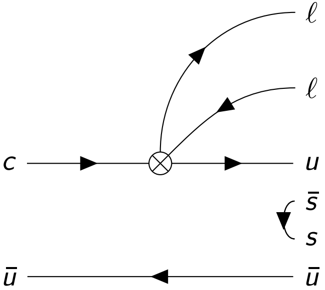

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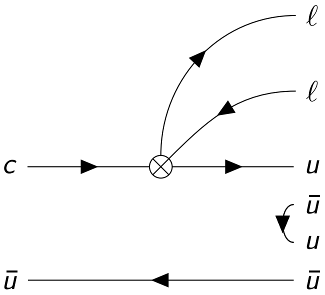
- $D^0 \to K^+K^-\ell\ell$
- $D^0 \to \pi^0\pi^0\ell\ell$



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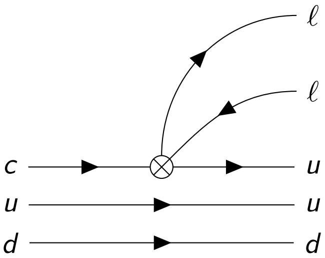
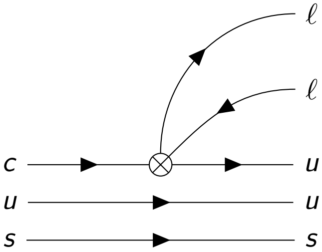
- $D^0 \to \pi^+\pi^-\ell\ell$
- $D^0 \to K^+K^-\ell\ell$
- $D^0 \to \pi^0\pi^0\ell\ell$
- $\Lambda_c \to p\ell\ell$

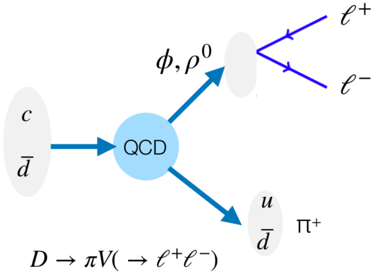


Rare charm decays

- $D^0 \to \ell\ell$
- $D^+ \to \pi^+\ell\ell$
- $D_s^+ \to K^+\ell\ell$
- $D^0 \to \pi^+\pi^-\ell\ell$
- $D^0 \to K^+K^-\ell\ell$
- $D^0 \to \pi^0\pi^0\ell\ell$
- $\Lambda_c \to p\ell\ell$
- $\Xi_c \to \Sigma\ell\ell$



- SM contributions dominated by long range dynamics
  $\mathcal{B}^{\mathrm{SM}}(D \to \pi \ell^+ \ell^-) \approx \mathcal{B}(D \to \pi V(\to \ell^+ \ell^-))$
- Parametrized by a sum of Breit-Wigner contributions (fit from data)
  $$C_9^R(q^2) = a_\omega e^{i\delta_\omega} \left(\frac{1}{q^2 - m_\omega^2 + i m_\omega \Gamma_\omega} - \frac{3}{q^2 - m_\rho^2 + i m_\rho \Gamma_\rho} \right) + \frac{a_\phi e^{i\delta_\phi}}{q^2 - m_\phi^2 + i m_\phi \Gamma_\phi}.$$
  $$C_P^R(q^2) = \frac{a_\eta e^{i\delta_\eta}}{q^2 - m_\eta^2 + i m_\eta \Gamma_\eta} + \frac{a_{\eta'}}{q^2 - m_{\eta'}^2 + i m_{\eta'} \Gamma_{\eta'}}$$



- Parameters in C_9^R, C_P^R are main source of uncertainties
- Process dependent 1909.11108, 1805.08516

	a_ρ / GeV^2	a_ϕ / GeV^2	a_η / GeV^2	$a_{\eta'}$ / GeV^2
$D^+ \to \pi^+$	~ 0.2	~ 0.2	$\sim 6 \times 10^{-4}$	$\sim 8 \times 10^{-4}$
$D^0 \to \pi^0$	~ 0.9	~ 0.3	$\sim 5 \times 10^{-4}$	$\sim 8 \times 10^{-4}$
$D_s^+ \to K^+$	~ 0.5	~ 0.1	$\sim 6 \times 10^{-4}$	$\sim 7 \times 10^{-4}$
$D^0 \to \pi^+\pi^-$	~ 0.7	~ 0.3	$\sim 1 \times 10^{-3}$	$\sim 1 \times 10^{-3}$
$D^0 \to K^+K^-$	~ 0.7	–	$\sim 3 \times 10^{-4}$	–

- Parameters in C_9^R, C_P^R are main source of uncertainties
- Process dependent 1909.11108, 1805.0[illegible]

	[illegible]	[illegible]	[illegible]	[illegible] / GeV^2
$D^+ \to \pi^+$	[illegible]	[illegible]	[illegible]	$\sim 8 \times 10^{-4}$
$D^0 \to \pi^0$	[illegible]	[illegible]	$\sim 5 \times 10^{-4}$	$\sim 8 \times 10^{-4}$
$D_s^+ \to K^+$	[illegible]	~ 0.1	$\sim 6 \times 10^{-4}$	$\sim 7 \times 10^{-4}$
$D^0 \to \pi^+\pi^-$	[illegible]	~ 0.3	$\sim 1 \times 10^{-3}$	$\sim 1 \times 10^{-3}$
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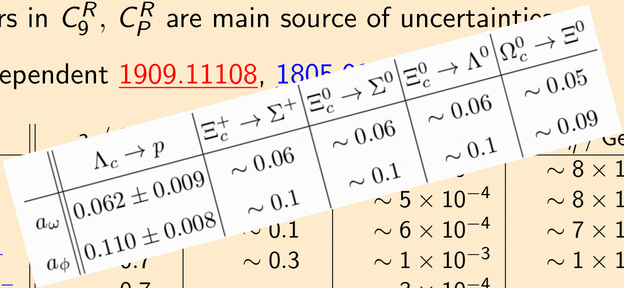

	$\Lambda_c \to p$	$\Xi_c^+ \to \Sigma^+$	$\Xi_c^0 \to \Sigma^0$	$\Xi_c^0 \to \Lambda^0$	$\Omega_c^0 \to \Xi^0$
a_ω	0.062 ± 0.009	~ 0.06	~ 0.06	~ 0.06	~ 0.05
a_ϕ	0.110 ± 0.008	~ 0.1	~ 0.1	~ 0.1	~ 0.09

2107.13010

- Parameters in C_9^R, C_P^R are main source of uncertainties
- Process dependent 1909.11108, 1805.0[illegible]

	$\Lambda_c \to p$	$\Xi_c^+ \to \Sigma^+$	$\Xi_c^0 \to \Sigma^0$	$\Xi_c^0 \to \Lambda^0$	$\Omega_c^0 \to \Xi^0$
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	[illegible]	[illegible]	[illegible]	[illegible] / GeV^2
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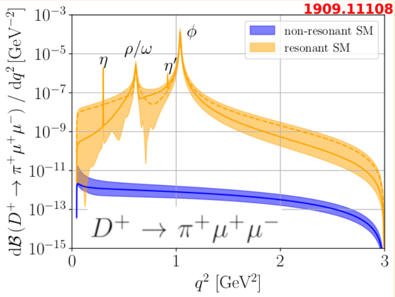
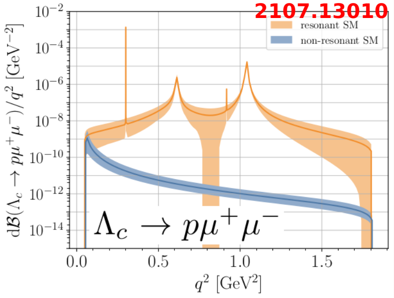
- With more data model parameters (a_i, δ_i) can be constrained and the model can be improved.

Resulting differential branching ratios





- Rare charm decays observed only at the resonances, for the rest of the signal region U.L. are available at 90 % C.L. (see 2011.09478)
  - $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$
  - $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 6.7 \times 10^{-8}$
  - $\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7}$
  - $\mathcal{B}(\Lambda_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$
  - **New results already presented at implications workshop**

Direct bounds on WC's from $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$, $\mathcal{B}(D^0 \to \mu^+\mu^-)$ imply

- $C_{S,P} \lesssim \mathcal{O}(0.1) \quad C_{7,9,10,T,T5} \lesssim \mathcal{O}(1)$

NP searches in branching ratios are challenging.

Instead define null test observables where

Signal $\leftrightarrow$ NP

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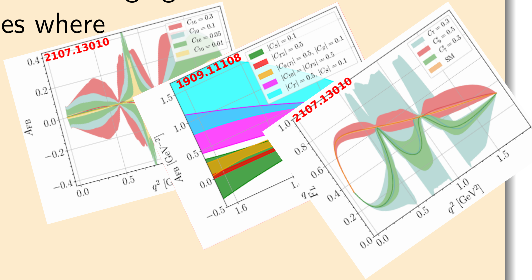
Overview null test strategies

NP searches in branching ratios are challenging.

Instead define null test observables where

Signal $\leftrightarrow$ NP

- Angular observables



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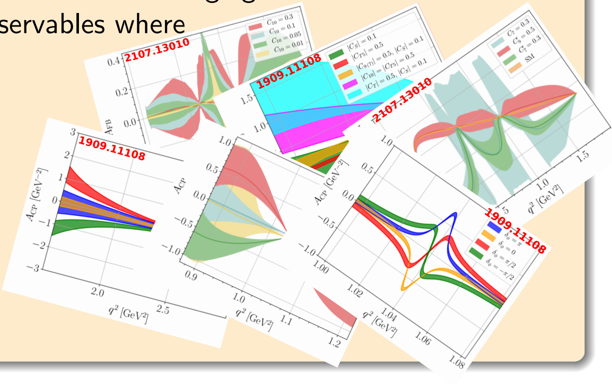
Instead define null test observables where

Signal $\leftrightarrow$ NP

- Angular observables
- CP–asymmetries



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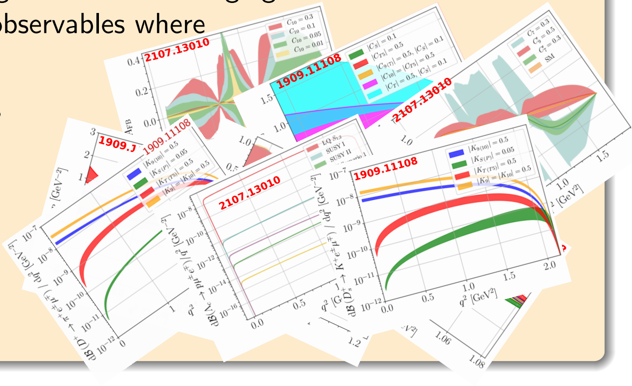
Instead define null test observables where

$$\text{Signal} \leftrightarrow \text{NP}$$

- Angular observables
- CP–asymmetries
- LFV



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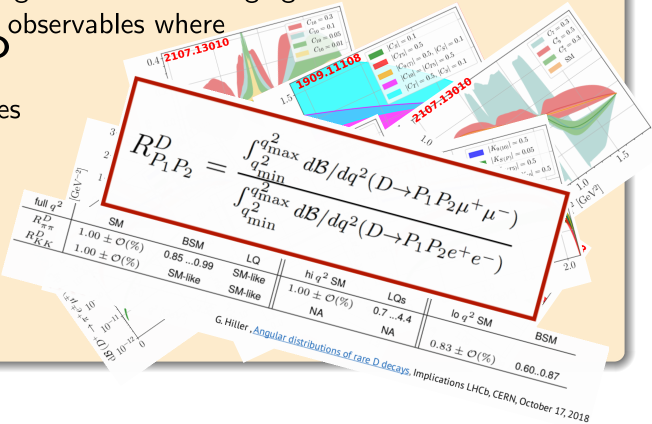


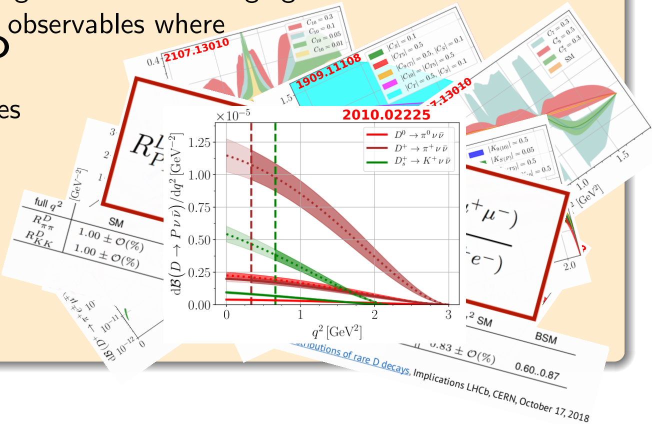
Overview null test strategies

NP searches in branching ratios are challenging.

Instead define null test observables where

Signal $\leftrightarrow$ NP

- Angular observables
- CP–asymmetries
- LFV
- LU ratios
- Dineutrino modes



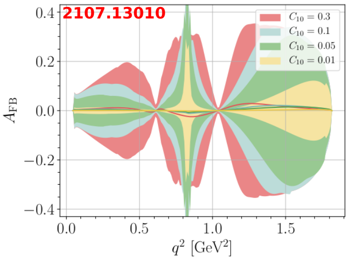
Part II - Null test observables

$\Lambda_c \to p\mu^+\mu^-$ decay distribution:

$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell} = \frac{3}{2}\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right),$$

$$A_{FB} = \frac{1}{d\Gamma/dq^2}\left[\int_0^1 - \int_{-1}^0\right]\frac{d\Gamma}{dq^2 d\cos\theta_\ell}\, d\cos\theta_\ell = \frac{3}{2}\frac{K_{1c}}{2K_{1ss}+K_{1cc}}.$$

$K_{1c} \sim C_9 C_{10}$, $C_9' C_{10}'$ and $C_7^{(\prime)} C_{10}^{(\prime)}$ interference terms $\Rightarrow$ **no SM**.



Forward-backward asymmetry

$\Lambda_c \to p\mu^+\mu^-$ decay distribution:

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$$A_{\mathrm{FB}} = \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\left[\int_0^1 - \int_{-1}^0\right]\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell}\,\mathrm{d}\cos\theta_\ell = \frac{3}{2}\frac{K_{1c}}{2K_{1ss}+K_{1cc}}.$$

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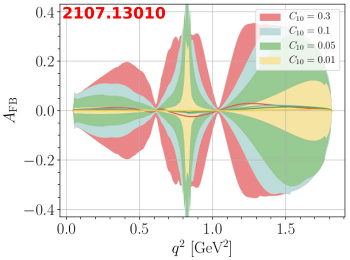
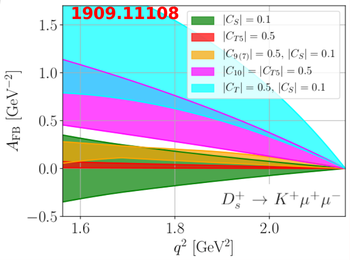
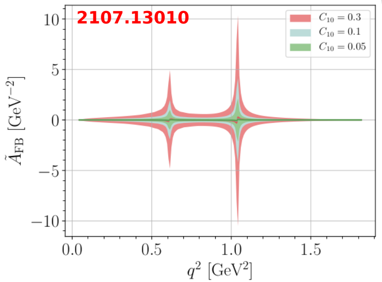
Complementary results in $D \to P\mu^+\mu^-$ (Normalized to integrated rate)

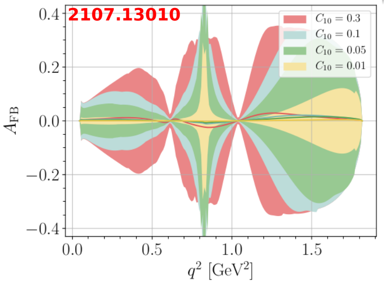




Normalization matters

- $\tilde{A}_{\mathrm{FB}} = \frac{3}{2}\frac{K_{1c}}{\Gamma}$ with $\Gamma = \int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} (2\,K_{1ss} + K_{1cc})$
- $A_{\mathrm{FB}} = \frac{3}{2}\frac{K_{1c}}{\mathrm{d}\Gamma/\mathrm{d}q^2}$ with $\mathrm{d}\Gamma/\mathrm{d}q^2 = 2\,K_{1ss} + K_{1cc}$
- Resonance enhancement

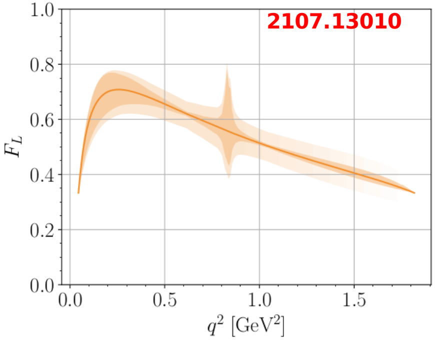


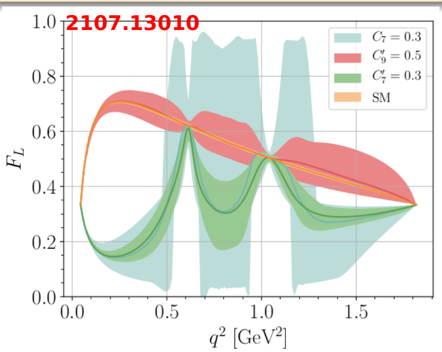


Fraction of longitudinally polarized dimuons

$$F_L = \frac{2\,K_{1ss} - K_{1cc}}{2\,K_{1ss} + K_{1cc}}$$

No null test, but cancellation of hadronic uncertainties in the SM and highly sensitive to $C_7^{(\prime)}$.





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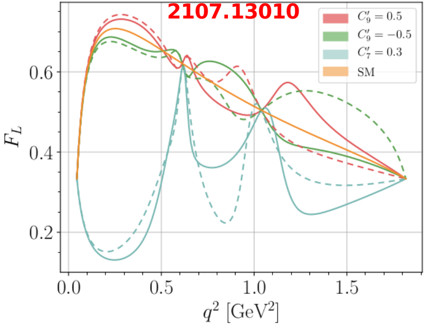
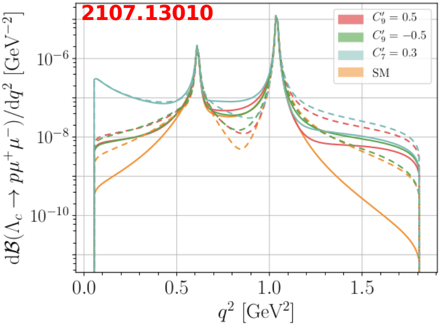
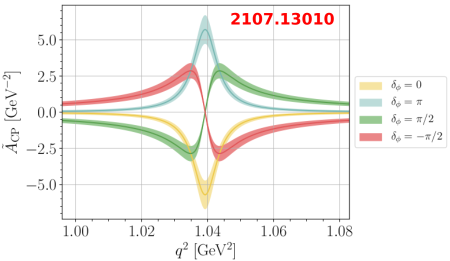


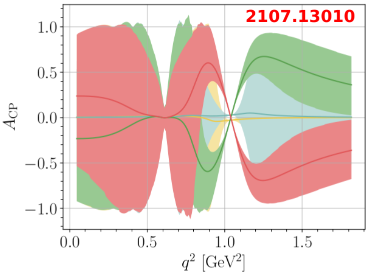


CP–asymmetries

$$\tilde{A}_{\text{CP}}(q^2) = \frac{1}{\Gamma + \bar{\Gamma}}\left(\frac{d\Gamma}{dq^2} - \frac{d\bar{\Gamma}}{dq^2}\right) \quad \text{with} \quad \Gamma = \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\Gamma}{dq^2} dq^2 \quad \text{or} \quad A_{\text{CP}}(q^2) = \frac{\frac{d\Gamma}{dq^2} - \frac{d\bar{\Gamma}}{dq^2}}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}}$$

- Strong phase from resonances needed $\longrightarrow$ measurement around the ϕ resonance. S. Fajfer and N. Kosnik 1208.0759
- NP weak phase needed. $\longrightarrow$ benchmark $C_9 = 0.5 \exp(i\pi/4)$.
- Binning necessary.





Part III - Dineutrino modes

SU(2)–link relating dineutrino and dilepton modes

- $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$-invariant effective theory (1008.4884)

$$\mathcal{L}^{\mathrm{LO}}_{\mathrm{SMEFT}} \supset \frac{C^{(1)}_{\ell q}}{v^2} \bar{Q}\gamma_\mu Q \, \bar{L}\gamma^\mu L + \frac{C^{(3)}_{\ell q}}{v^2} \bar{Q}\gamma_\mu \tau^a Q \, \bar{L}\gamma^\mu \tau^a L + \frac{C_{\ell u}}{v^2} \bar{U}\gamma_\mu U \, \bar{L}\gamma^\mu L + \frac{C_{\ell d}}{v^2} \bar{D}\gamma_\mu D \, \bar{L}\gamma^\mu L$$

- C_A^P and K_A^P matched via $\mathrm{SU}(2)_L$-components in gauge basis

$$C_L^U = K_L^D = C^{(1)}_{\ell q} + C^{(3)}_{\ell q} \qquad C_R^U = K_R^U = C_{\ell u}$$
$$C_L^D = K_L^U = C^{(1)}_{\ell q} - C^{(3)}_{\ell q} \qquad C_R^D = K_R^D = C_{\ell d}$$

- going to *mass basis*: $Q_\alpha = \left(u_{L\,\alpha},\, V_{\alpha\beta} d_{L\,\beta}\right), \quad L_i = \left(\nu_{L\,i},\, W^*_{ki} \ell_{L\,k}\right)$
  (V: CKM, W: PMNS)

$$\boxed{\mathcal{C}_L^U = W^\dagger \, \mathcal{K}_L^D \, W + \mathcal{O}(\lambda), \quad \mathcal{C}_R^U = W^\dagger \, \mathcal{K}_R^U \, W}$$

Link dineutrino to charged dilepton modes via $SU(2)_L$ in SMEFT 2007.05001, 2010.02225

$$\mathcal{B} \propto \sum_{\nu=i,j} \left(|\mathcal{C}_L^{U ij}|^2 + |\mathcal{C}_R^{U ij}|^2 \right) = \mathrm{Tr}\left[\mathcal{C}_L^{U} \mathcal{C}_L^{U\dagger} + \mathcal{C}_R^{U} \mathcal{C}_R^{U\dagger} \right]$$

$$= \mathrm{Tr}\left[\mathcal{K}_L^{D} \mathcal{K}_L^{D\dagger} + \mathcal{K}_R^{U} \mathcal{K}_R^{U\dagger} \right] + \mathcal{O}(\lambda) = \sum_{\ell=i,j} \left(|\mathcal{K}_L^{D ij}|^2 + |\mathcal{K}_R^{U ij}|^2 \right) + \mathcal{O}(\lambda)$$

- **SU(2) relates up, down, neutrinos and charged leptons.**

$c \to u\,\ell^+\ell^-$ ⟶ $c \to u\,\nu\bar{\nu}$ ⟵ $s \to d\,\ell^+\ell^-$

⋆ **Independent of PMNS matrix and subleading $\mathcal{O}(\lambda)$ corrections!**

⋆ **Prediction of dineutrino rates for different leptonic flavor structures $\mathcal{K}_{L,R}^{ij}$ can be probed with lepton-specific measurements!**

Possible leptonic flavor structures for $\mathcal{K}_{L,R}^{ij}$

i) **Lepton-universality (LU).**

$$\begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix}$$

ii) **Charged lepton flavor conservation (cLFC).**

$$\begin{pmatrix} k_{11} & 0 & 0 \\ 0 & k_{22} & 0 \\ 0 & 0 & k_{33} \end{pmatrix}$$

iii) $\mathcal{K}_{L,R}^{ij}$ **arbitrary.**

$$\begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix}$$

Upper limits on dineutrino modes can probe lepton unversality!

- **Bounds on lepton specific WCs for $\ell, \ell' = e, \mu, \tau$.** 2003.12421, 2002.05684

	$\lvert\mathcal{K}_A^{P\ell\ell'}\rvert$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$s \to d$	$\lvert\mathcal{K}_L^{D\ell\ell'}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
$c \to u$	$\lvert\mathcal{K}_R^{U\ell\ell'}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1

- $\mathcal{B} \propto x = \sum_{\ell,\ell'} \left(\lvert\mathcal{K}_L^{D\ell\ell'}\rvert^2 + \lvert\mathcal{K}_R^{U\ell\ell'}\rvert^2 \right) + \mathcal{O}(\lambda) = \sum_{\ell,\ell'} R^{\ell\ell'} + \mathcal{O}(\lambda)$

$x = 3\, R^{\mu\mu} \lesssim 34\,,$ **(Lepton Universality)**

$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 196\,,$ **(charged Lepton Flavor Conservation)**

$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2\left(R^{e\mu} + R^{e\tau} + R^{\mu\tau}\right) \lesssim 716.$

LU is fixed by the most stringent bound (muons) and the $\mathcal{O}(\lambda)$ corrections are included

$$\mathcal{B}(h_c \to F\,\nu\bar{\nu}) = A_+^{h_c F}\, x_+ + A_-^{h_c F}\, x_- \,, \quad x_\pm = \sum_{i,j} |\mathcal{C}_L^{Uij} \pm \mathcal{C}_R^{Uij}|^2 < 2\,x\,.$$

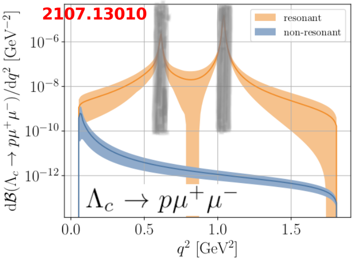
$N_i = \eta_{\text{eff}}\, \mathcal{B}_i\, N(h_c)$, $N(c\bar{c})_{\text{Belle II}} = 65 \cdot 10^9$ for 50 ab^{-1}, $N(c\bar{c})_{\text{FCC-ee}} = 550 \cdot 10^9$.

$h_c \to F$	$\mathcal{B}^{\max}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\max}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\max}$ $[10^{-6}]$	$N^{\max}_{\text{LU}}/\eta_{\text{eff}}$	$N^{\max}_{\text{cLFC}}/\eta_{\text{eff}}$	$N^{\max}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	6.1	3.5	13	47 k (395 k)	270 k (2.3 M)	980 k (8.3 M)
$D^+ \to \pi^+$	25	14	52	77 k (650 k)	440 k (3.7 M)	1.6 M (14 M)
$D_s^+ \to K^+$	4.6	2.6	9.6	6 k (50 k)	34 k (290 k)	120 k (1.1 M)
$D^0 \to \pi^0\pi^0$	1.5	0.8	3.1	11 k (95 k)	64 k (540 k)	230 k (2.0 M)
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9	22 k (180 k)	120 k (1.0 M)	450 k (3.8 M)
$D^0 \to K^+K^-$	0.03	0.02	0.06	0.2 k (1.9 k)	1.3 k (11 k)	4.8 k (40 k)
$\Lambda_c^+ \to p^+$	18	11	39	14 k (120 k)	82 k (700 k)	300 k (2.6 M)
$\Xi_c^+ \to \Sigma^+$	36	21	76	28 k (240 k)	160 k (1.4 M)	590 k (5.0 M)
$D^0 \to X$	12	6.8	25	91 k (770 k)	520 k (4.4 M)	1.9 M (16 M)
$D^+ \to X$	30	17	63	94 k (800 k)	540 k (4.6 M)	2.0 M (17 M)
$D_s^+ \to X$	13	7.3	27	17 k (140 k)	95 k (810 k)	350 k (2.9 M)

(EFT breakdown) $> \mathcal{B}^{\max}$ (LFV) $> \mathcal{B}^{\max}_{\text{cLFC}}$ (LU violation) $> \mathcal{B}^{\max}_{\text{LU}}$

- Rare charm decays are dominated by long-distance resonance contributions
- NP can be probed in **clean** null test observables
- Null test observables make use of resonance enhancement
- Collaborative partnership between theory and experiment enables improvements in future predictions

BACKUP



- LHCb upper limit at 90 % C.L. with ± 40 MeV cuts around known resonance masses, then extrapolated to full q^2 region

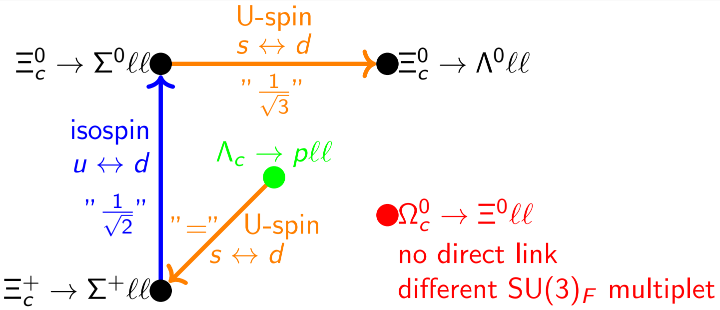
$$\mathcal{B}_{\mathrm{LHCb}}(\Lambda_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$$

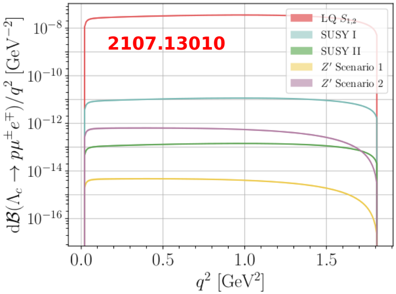
- Including form factor and resonance uncertainties and integrating the LHCb search region

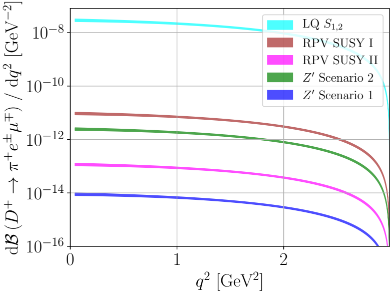
$$\mathcal{B}^{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-) = (1.9^{+1.8}_{-1.5}) \times 10^{-8}$$
$$\mathcal{B}^{\mathrm{SM}}(\Xi_c^+ \to \Sigma^+\mu^+\mu^-) \sim 1.8 \times \mathcal{B}^{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-)$$
$$\mathcal{B}^{\mathrm{SM}}(\Xi_c^0 \to \Sigma^0\mu^+\mu^-) \sim 0.4 \times \mathcal{B}^{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-)$$
$$\mathcal{B}^{\mathrm{SM}}(\Omega_c^0 \to \Xi^0\mu^+\mu^-) \sim 1.3 \times \mathcal{B}^{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-)$$

A note on form factors

- Form factors are availbale for $\Lambda_c \to p\mu^+\mu^-$ from Lattice QCD (see 1712.05783)
- No results for other decay modes (from the lattice) available yet.
- Use $SU(3)_F$ flavor symmetries to relate modes

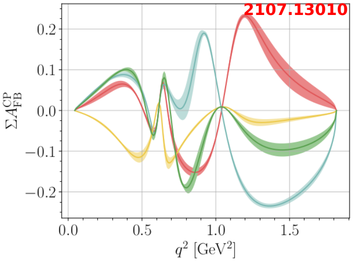


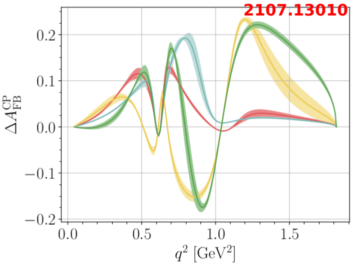


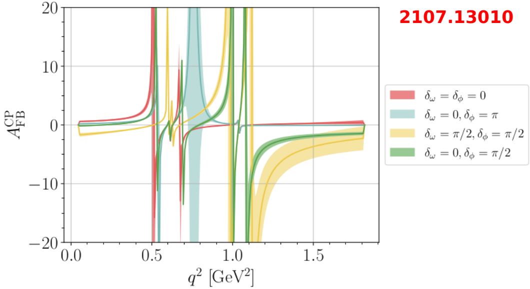


LQ's ($K_9' = K_{10}' = 0.5$),
SUSY + R-parity violation ($K_9 = -K_{10} = 0.009$),
SUSY no R-parity violation ($K_9 = -K_{10} = 0.001$),
Z' 1 ($K_9 = K_9' = -K_{10} = -K_{10}' = 1.4 \cdot 10^{-4}$),
Z' 2 ($K_9 = K_9' = -K_{10} = -K_{10}' = 2.3 \cdot 10^{-4}$).

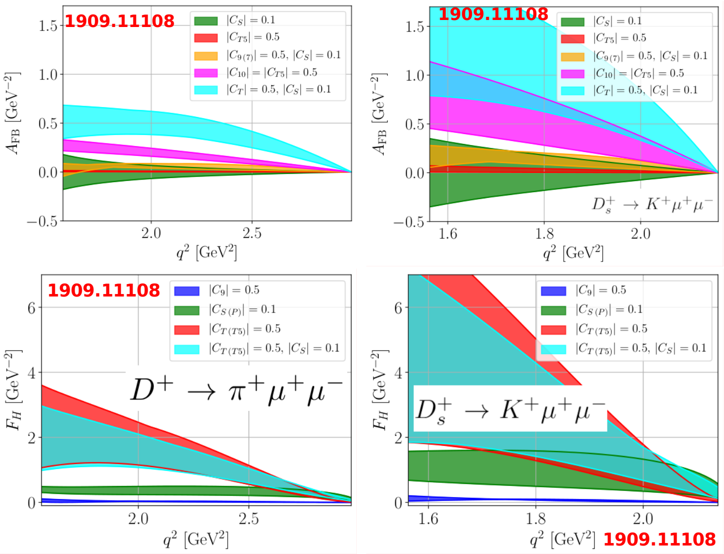
$A_{\text{FB}}^{\text{CP}}$ for baryons







Angular observables in $D \to P\ell\ell$



$$R_\pi^D = \int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(D \to \pi\mu^+\mu^-)}{dq^2} dq^2 \Big/ \int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(D \to \pi e^+ e^-)}{dq^2} dq^2$$

R_π^D	SM	$\lvert C_9 \rvert = 0.5$	$\lvert C_{10} \rvert = 0.5$	$\lvert C_9 \rvert = \pm \lvert C_{10} \rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like
low q^2	$0.95 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$
high q^2	$1.00 \pm \mathcal{O}(\%)$	$0.2 \ldots 11$	$3 \ldots 7$	$2 \ldots 17$

1909.11108

LU ratios

$$R_\pi^D = \int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{d\mathcal{B}(D \to \pi\mu^+\mu^-)}{dq^2} dq^2 \Big/ \int^{q^2} \ldots dq^2$$

$$R_p^{\Lambda_c} = \int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{d\mathcal{B}(\Lambda_c \to p\mu^+\mu^-)}{dq^2} dq^2 \Big/ \int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{d\mathcal{B}(\Lambda_c \to pe^+e^-)}{dq^2} dq^2$$

	SM	$\lvert C_9^\mu\rvert = 0.5$	$\lvert C_{10}^\mu\rvert = 0.5$	$\lvert C_9^\mu\rvert = \lvert C_{10}^\mu\rvert = 0.5$	$\lvert C_9'^\mu\rvert = 0.5$	$\lvert C_{10}'^\mu\rvert = 0.5$	$\lvert C_9'^\mu\rvert = \lvert C_{10}'^\mu\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like	SM-like	SM-like	SM-like
low q^2	$0.94 \pm \mathcal{O}(\%)$	$7.5 \ldots 20$	$4.4 \ldots 13$	$11 \ldots 32$	$4.6 \ldots 14$	$4.4 \ldots 13$	$8.2 \ldots 26$
high q^2	$1.00 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$

2107.13010

$$R^D_\pi = \int_{q^2_{\min}}^{q^2_{\max}} \ldots \, dq^2 \;/\; \int^{q^2} \ldots \, dq^2$$

$$R^D_{P_1P_2} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2(D \to P_1P_2\mu^+\mu^-)}{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2(D \to P_1P_2e^+e^-)}$$

$$\int^{q^2_{\max}} \frac{d\mathcal{B}(\Lambda_c \to pe^+e^-)}{dq^2} dq^2$$

full q^2	SM	BSM	LQ	hi q^2 SM	LQs	lo q^2 SM	BSM
$R^D_{\pi\pi}$	$1.00 \pm \mathcal{O}(\%)$	0.85 ...0.99	SM-like	$1.00 \pm \mathcal{O}(\%)$	0.7 ...4.4	$0.83 \pm \mathcal{O}(\%)$	0.60..0.87
R^D_{KK}	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	NA	NA		

	SM		$\lvert C_9'^{\mu}\rvert = \lvert C_{10}'^{\mu}\rvert = 0.5$
			SM-like
full q^2	$1.00 \pm \mathcal{O}(\%)$	$7.5 \ldots 20$	$8.2 \ldots 26$
low q^2	$0.94 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$
high q^2	$1.00 \pm \mathcal{O}(\%)$		

G. Hiller, Angular distributions of rare D decays, Implications LHCb, CERN, October 17, 2018

1805.08516

$$\frac{d^5\Gamma}{dq^2 dp^2 d\cos\theta_\mu d\cos\theta_h d\phi} =$$

$$\begin{aligned}
\text{(enter } \mathcal{B}\text{)} \quad & \underline{I_1} + \underline{I_2} \cdot \cos 2\theta_\mu \\
& + \underline{I_3} \cdot \sin^2\theta_\mu \cos 2\phi + \underline{I_4} \cdot \sin 2\theta_\mu \cos\phi \\
\text{(Null tests)} \quad & + \boxed{I_5} \cdot \sin\theta_\mu \cos\phi + \boxed{I_6} \cdot \cos\theta_\mu + \underline{I_7} \cdot \sin\theta_\mu \sin\phi \\
& + \boxed{I_8} \cdot \sin 2\theta_\mu \sin\phi + \boxed{I_9} \cdot \sin^2\theta_\mu \sin 2\phi
\end{aligned}$$

Note:

- $I_i = I_i(q^2, p^2, \cos\theta_h)$
- $\underline{I_{1,2,3,4,7} \text{ CP–even}}$
- $\boxed{I_{5,6,8,9} \text{ CP–odd}}$

$$\frac{d^5\Gamma}{dq^2 dp^2 d\cos\theta_\mu d\cos\theta_h d\phi} =$$

(enter $\mathcal{B}$) $\underline{I_1} + \underline{I_2} \cdot \cos 2\theta_\mu$

$+\underline{I_3} \cdot \sin^2\theta_\mu \cos 2\phi + \underline{I_4} \cdot \sin 2\theta_\mu \cos\phi$

(Null tests) $+\boxed{I_5} \cdot \sin\theta_\mu \cos\phi + \boxed{I_6} \cdot \cos\theta_\mu + \underline{I_7} \cdot \sin\theta_\mu \sin\phi$

$+\boxed{I_8} \cdot \sin 2\theta_\mu \sin\phi + \boxed{I_9} \cdot \sin^2\theta_\mu \sin 2\phi$

Note:

- $I_i = I_i(q^2, p^2, \cos\theta_h)$
- $I_{1,2,3,4,7}$ CP–even
- $I_{5,6,8,9}$ CP–odd

Strategy:

- Measure p^2, $\cos\theta_h$ integrated and $1/\Gamma$ normalized $\langle I_i \rangle(q^2)$
- Measure D^0 and $\overline{D^0}$ seperately

$$\frac{d^5\Gamma}{dq^2 dp^2 d\cos\theta_\mu d\cos\theta_h d\phi} =$$

(enter $\mathcal{B}$) $\underline{I_1} + \underline{I_2} \cdot \cos 2\theta_\mu$

$+\underline{I_3} \cdot \sin^2\theta_\mu \cos 2\ldots$

(Null tests) $\ldots\theta_\mu + \underline{I_7} \cdot \sin\theta_\mu \sin\phi$

$\ldots_\mu \sin\phi + \boxed{I_9} \cdot \sin^2\theta_\mu \sin 2\phi$

I_5, I_6, I_7 vanish in absence of axial vector couplings, $C_{10}^{(\prime)} \overset{\text{SM}}{=} 0$

(not usefull in B-decays, $I_5^{\text{SM}} \propto P_5^{\prime\,\text{SM}}(B \to K^* \ell\ell) \neq 0$)

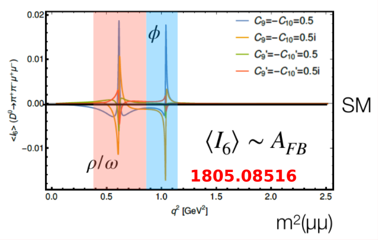
N…

- $I_i = I_i(q^2, p^2, \cos\theta_h)$
- $\underline{I_{1,2,3,4,7}\ \text{CP–even}}$
- $\boxed{I_{5,6,8,9}\ \text{CP–odd}}$

Strategy:

- Measure p^2, $\cos\theta_h$ integrated and $1/\Gamma$ normalized $\langle I_i\rangle(q^2)$
- Measure D^0 and $\overline{D^0}$ seperately

- Define asymmetries $A_i = 2\frac{I_i - \overline{I}_i}{\Gamma + \overline{\Gamma}} = \frac{I_i - \overline{I}_i}{\Gamma_{\text{ave}}}$
- Caution with I_i being CP–even or CP–odd
- $\langle I_{5,6,7} \rangle^{\text{SM}} = 0$
- $A_i^{\text{SM}} = 0$ for $i = 2, \ldots, 9$
- Resonance enhancement!



	$C_9 = -C_{10} = \pm 0.5i$	$C_9' = -C_{10}' = \pm 0.5i$
$\langle A_5 \rangle$	$[-0.04, 0.04]$	$[-0.03, 0.03]$
$\langle A_6 \rangle$	$[-0.06, 0.05]$	$[-0.06, 0.06]$
$\langle A_8 \rangle$	$[-0.02, 0.02]$	$[-0.02, 0.02]$
$\langle A_9 \rangle$	$[-0.03, 0.03]$	$[-0.03, 0.03]$

Upper limits on x from high-p_T

$$\mathcal{C}_L^{U_{12}} = W^\dagger \mathcal{K}_L^{D_{12}} W + \lambda\, W^\dagger (\mathcal{K}_L^{D_{22}} - \mathcal{K}_L^{D_{11}}) W + \mathcal{O}(\lambda^2)\,, \qquad \mathcal{C}_R^{U_{12}} = W^\dagger \mathcal{K}_R^{U_{12}} W$$

	$\lvert\bar{\mathcal{K}}_A^{P\ell\ell'}\rvert$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$d \to d$	$\lvert\mathcal{K}_{L,R}^{D_{11}\ell\ell'}\rvert$	2.8	1.5	5.5	1.1	3.3	3.6
$s \to s$	$\lvert\mathcal{K}_{L,R}^{D_{22}\ell\ell'}\rvert$	9.0	4.9	17	5.2	17	18
$s \to d$	$\lvert\bar{\mathcal{K}}_{L,R}^{D_{12}\ell\ell'}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
$c \to u$	$\lvert\bar{\mathcal{K}}_{L,R}^{U_{12}\ell\ell'}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1

(2003.12421), (2002.05684)

	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$R^{\ell\ell'}$	21	6.0	77	6.6	59	70
$\delta R^{\ell\ell'}$	19	5.4	69	5.7	55	63
$r^{\ell\ell'}$	39	11	145	12	115	133

with $r^{\ell\ell'} = R^{\ell\ell'} + \delta R^{\ell\ell'}$

$$R^{\ell\ell'} = \left|\mathcal{K}_L^{D_{12}\ell\ell'}\right|^2 + \left|\mathcal{K}_R^{U_{12}\ell\ell'}\right|^2,$$

$$R_\pm^{\ell\ell'} = \left|\mathcal{K}_L^{D_{12}\ell\ell'} \pm \mathcal{K}_R^{U_{12}\ell\ell'}\right|^2,$$

$$\delta R^{\ell\ell'} = 2\,\lambda\,\Re \mathcal{K}_L^{D_{12}\ell\ell'}\,\mathcal{K}_L^{D_{22}\ell\ell'\,*} - \mathcal{K}_L^{D_{12}\ell\ell'}\mathcal{K}_L^{D_{11}\ell\ell'\,*}$$

$$x = \sum_{\ell,\,\ell'} \left(R^{\ell\ell'} + \delta R^{\ell\ell'}\right)\,, \quad x_\pm = \sum_{\ell,\,\ell'} R_\pm^{\ell\ell'}$$

construct bounds on $x = \frac{x_+ + x_-}{2}$, with $x^\pm \leq 2\,x$,

$$x = 3\,r^{\mu\mu} \lesssim 34\,, \quad \text{(LU)}$$

$$x = r^{ee} + r^{\mu\mu} + r^{\tau\tau} \lesssim 196\,, \quad \text{(cLFC)}$$

$$x = r^{ee} + r^{\mu\mu} + r^{\tau\tau} + 2\,(r^{e\mu} + r^{e\tau} + r^{\mu\tau}) \lesssim 716\,.$$